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Co-existence, Competition and Interference of Bluetooth and WLAN

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Abstract— **Bluetooth is a technology, which uses a short-range radio link to exchange information, enabling wireless connectivity between mobile phones, mobile PCs and other peripherals. On the other hand, The Wireless Local Area Network (WLAN) provides an alternative to the traditional LANs based on twisted pair, coaxial cable, and optical fiber. Bluetooth and WLAN cause interference with each other, increasingly as they approach each other. Bluetooth causes more interference with WLAN than the other way around because of Bluetooth's faster hop rate (600 times faster). Co-existence is another problem that both Bluetooth & WLAN face. To allow co-existence, they must never use the same frequency at the same time. Bluetooth is designed for quick, short-range networks and features better power consumption, small protocol stack, robust data and voice transfer, which make it perfect for a WPAN (Wireless Personal Area Network) but limited in terms of WLAN (Wide Local Area Network).**

This paper presents an overview over the co-existence, competition and interference between Bluetooth & WLAN. For proper presentation of this, radio interfaces of both the technologies are discussed here also.

Keywords— **FHSS, DFSS, OFDM, GFSK, TDD, SCO, ACL, DSSS, pseudo-noise Sequence.**

I. INTRODUCTION

Bluetooth and WLAN pose an integration challenge as both technologies employ the same 2.4GHz to 2.4835 GHz unlicensed Industrial Scientific Medical (ISM) band [11]. Bluetooth uses a frequency hopping spread spectrum (FHSS) system in which the transmission band hops over 79 pre-defined 1 MHz channels. The hopping rate is roughly 1600 hops per second over a random pattern. However, as Bluetooth doesn't monitor the band before transmitting, it can easily interfere with other systems trying to use the same band. In this fashion, if WLAN is transmitting or receiving, when Bluetooth begins transmission, both air interfaces can fail to operate properly. In contrast to Bluetooth, WLAN does monitor its transmission band for other traffic before beginning to transmit.

WLAN (802.11) employs direct frequency spread spectrum (DFSS) and orthogonal frequency division multiplexing (OFDM) air interfaces, and occupies roughly a quarter of the 83.5MHz ISM band. Since WLAN (802.11) senses Bluetooth activity and doesn’t transmit if Bluetooth is active, WLAN service will be very seriously affected when Bluetooth interferes [1]. But, there are solutions. Non-collaborative coexistence solutions include adaptive fragmentation, which optimally adjusts packet sizes to minimize collisions and adaptive frequency hopping, in which the Bluetooth interface selectively hops to channels where it can successfully transmit. Collaborative coexistence solutions involve communication between the WLAN and Bluetooth interfaces in a handset and work to maximize the throughput of both interfaces while taking account of any quality of service (QoS) demands.

In this paper, the co-existence & interference between Bluetooth & WLAN is presented. For the proper analysis, radio interfaces and other aspects are also presented here. A possible solution towards the co-existence problem is discussed too.

II. BLUETOOTH RADIO INTERFACE

For Bluetooth transmission, 79 RF channels spaced 1 MHz apart are defined. The transmitting frequencies can be calculated by:

$$f = (2402 + k)MHz \qquad k = 0,........,78 \tag{1}$$

where, k = channel number.

For the transfer of the digital data symbols, the signal is modulated with Gaussian Frequency Shift Keying (GFSK). Here, each signal is either denoted as 1 (1) or -1 (0), but before the base band pulses it passes through a Gaussian filter which limits the spectral width.

$$v(t) = \sum_k S_k \, p(t - kT) \tag{2}$$

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$$|p(f)| = \begin{cases} 1 \\ \sqrt{\frac{1}{2}(1-\sin(\frac{\pi(2|f|T-1)}{2\beta}))} \\ 0 \end{cases} \qquad (3)$$

GFSK has a bandwidth-bit period product of 0.5, known as bandwidth time (BT) and the modulation index is between 0.28 and 0.35. The symbol timing is less than ±20ppm.

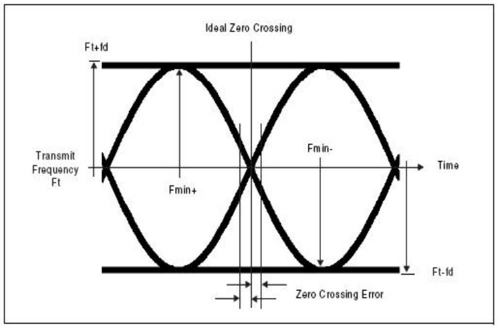

Fig 1: Ideal Zero Crossing GFSK

The minimum deviation of each transmission is $F_{\min} = \{F^{+}_{\min}; F^{-}_{\min}\}$, which corresponds to the sequence 1010. This shall be $\pm 80\%$ of the deviation of the sequence 00001111. The zero crossing error shall be less than ± ⅛ of a symbol period and is defined as the difference between the ideal symbol period and the actual crossing time. To combat interference and fading, Frequency Hopping Spread Spectrum technology (FHSS) is applied [10]. The Bluetooth channel is represented by a pseudo-random hopping sequence hopping through the 79 RF channels [8].

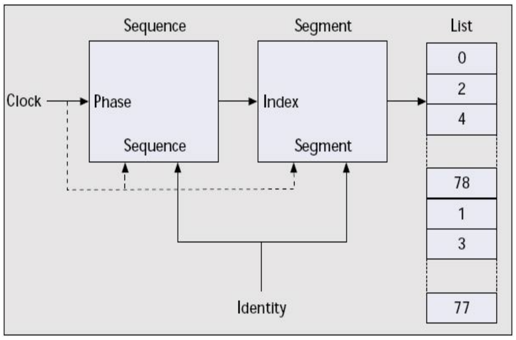

Fig 2: The Bluetooth hopping sequence generator

As seen in figure 2, the sequence is, selected by the unit identity the “Global ID” and the phase is determined by the system clock. The sequence is designed to cycle in about 23 hrs and the spreading of the sequence is 64 MHz for 32 consecutive hops [3].

For full-duplex transmission, Time-Division Duplex (TDD) scheme is used. Bluetooth uses frames to send information and each frame consists of one transmit packet and one receive packet. These frames can be multi-slotted with 1, 3 or 5 slots. Each slot represents a period of time of 625 µs. These multi-slot frames enable higher data rate as the header space can be reduced. For a single slot transmission, the maximum data rate is 172 Kbit/s while for a 5-slotted frame the maximum data rate is 721 Kbit/s [8].

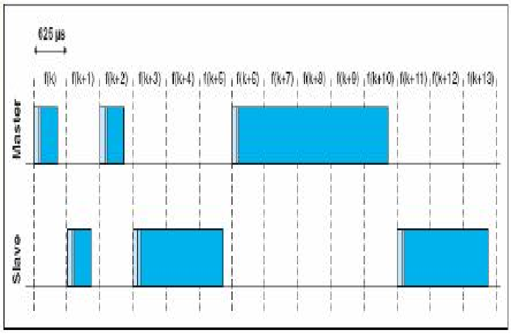

Fig 3: A multi-slot transmission between a master and a slave

Bluetooth can handle both circuit and packet switched links. Synchronous connection-oriented link, or SCO, is the circuit switched link and is used for the point-to-point transport between the master and a single slave. SCO carries mostly voice data. The traffic is employed during some regular intervals with reserved slots for synchronous transmission. The other link is asynchronous connection-less link, or ACL, which is the packet switched link. ACL can handle point-to-multi-point connections and there are no slots reserved for ACL traffic. Instead ACL uses the non-reserved slots to send information to a number of slaves.

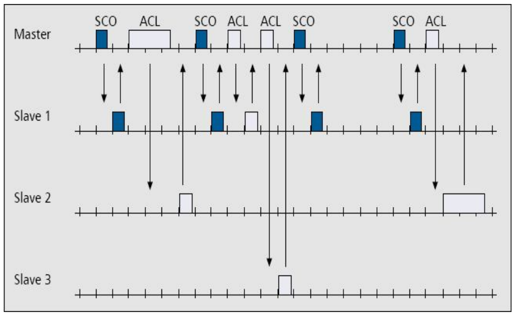

Fig 4: Traffic between two slaves and a master regarding SCO and ACL

III. WLAN RADIO INTERFACE

A Direct Sequence Spread Spectrum (DSSS) system spreads the baseband data by directly multiplying the baseband data pulses with a pseudo-noise sequence (PN) that’s produced by a pseudo-noise code generator [10]. A single pulse or a symbol of the PN waveform is called a chip. One data bit is therefore expressed by several chips and this "spreads" the data into a large coded stream that takes the full bandwidth of the channel. Interferences are expected to emerge only in a small frequency part of the channel. At the receiver, multiplication with the spreading waveform generates the data signal with its small bandwidth and smuts the interfering signal over the whole channel bandwidth. In 802.11b systems [2], the channel bandwidth is 22 MHz and a chipping rate of 11 MHz is used. For modulation Differential Quadrature Phase Shift Keying (D-QPSK) or Differential Binary Phase Shift Keying (D-BPSK) is applied.

TABLE 1
KEY CHARACTERISTICS OF IEEE 802.11

Bit Rate	Spreading	Modulation	Symbol Rate
11 Mbit/s	CCK	DQPSK	1.375 MSps
5.5 Mbit/s	CCK	DQPSK	1.375 MSps
2 Mbit/s	Barker	DQPSK	1.0 MSps
1 Mbit/s	Barker	DBPSK	1.0 MSps

Typical transfer rates for user data are 5 Mbit/s. For difficult propagation conditions (i.e. larger range, interference…), the system uses link adaptation to lower transfer rates. Table 2 gives an overview about the different data rates on the physical layer of 802.11b systems [2] and the corresponding maximum range for open environments (i.e., outdoor or large halls) and for “closed” environments (i.e. indoor):

TABLE 2
USE CASES (RANGE AND CAPACITY)

	11 Mbit/s	**5.5 Mbit/s**	**2 Mbit/s**	**1 Mbit/s**
Open environment; range up to	150 m	250 m	300 m	400 m
Closes environment, range up to	30 m	35 m	40 m	50 m

According to European regulations, in the ISM band, ranging from 2.400 to 2.4835 GHz, there are 13 overlapping channels with a separation of 5 MHz available for WLANs (with a very few exceptions in some countries). Avoiding interference the minimum distance between the centre frequencies is at least 25 MHz [9]. Therefore, up to three non-overlapping channels are available in the ISM band. Studies show that adjacent cells will not interfere with each other when the channel spacing uses channel center frequencies that are 15 MHz apart. The transmitted power of WLAN systems usually is 100 mW. At a data rate of 11 Mbit/s the receiver sensitivity should be at least-76 dBm.

IV. MUTUAL INTERFERENCES

In order to determine the degree to which the radios will cause harmful interference to each other, a number of assumptions are necessary. It is difficult, if not impossible, to define a “typical” network topology. User scenarios and even indoor propagation models can be rather subjective. However, by using some reasonable assumptions, analysis of the interference caused by co-location of the two radio types can proceed. These assumptions must include [4]:

- A network topology and user density.
- Propagation model.
- Network traffic loads for IEEE 802.11b and Bluetooth.

A simplified indoor propagation model has been proposed where Line-of-sight propagation is assumed for the first 8 meters. Beyond this point, path loss increases as a function of $\mathbf{r}^{\mathbf{n}}$, where $\mathbf{r}$ is range and $\mathbf{n} = 3.3$. This can be expressed in terms of decibels:

$$\begin{aligned} L_{path} &= 20\log(4\pi r/\lambda) \qquad r < 8m \qquad (4) \\ &= 58.3 + 33\log(r/8), \end{aligned}$$

where,

λ = free space wavelength @ 2.45 GHz (0.1224 m),
r = range (m).

Figure 5 shows some possible WLAN channels and the Bluetooth RF channels available in most European countries. Bluetooth is hopping over 79 RF channels with a bandwidth of 1 MHz. It can be estimated that a frequency hop of one active Bluetooth transmitter overlaps a WLAN channel with a probability of about 20% - 25%since the power density at the boarder of a WLAN channel decreases [5].

A. *Bluetooth interferes WLAN*

The impact of Bluetooth personal area networks on a WLAN system is investigated through some assumptions. A high density environment is postulated. Traffic loads are assumed for the Bluetooth piconets. In fact, the following assumptions were made [15]:

- WLAN mobile station may be located up to 20 meters from the WLAN access point. The average density is one WLAN mobile station every 25 sq. meters.
- The transmitter power for WLAN mobile nodes and the WLAN access point is +20dBm.
- There is one Bluetooth piconet co-located with each WLAN node.
- The Bluetooth piconet consists of two or more Bluetooth devices which are capable of establishing at least a point-to-point link.

From the analysis, the points which came out clear are:

- The degree of interference experienced in any installation is dependent on local propagation conditions, the density of Bluetooth piconets, and Bluetooth piconet loading.
- IEEE 802.11b DSSS WLAN susceptibility to Bluetooth interference increases as a function of range from the DSSS wireless node to the DSSS AP [6].
- IEEE 802.11b DSSS Hi Rate systems show graceful degradation in the presence of significant levels of Bluetooth interference.

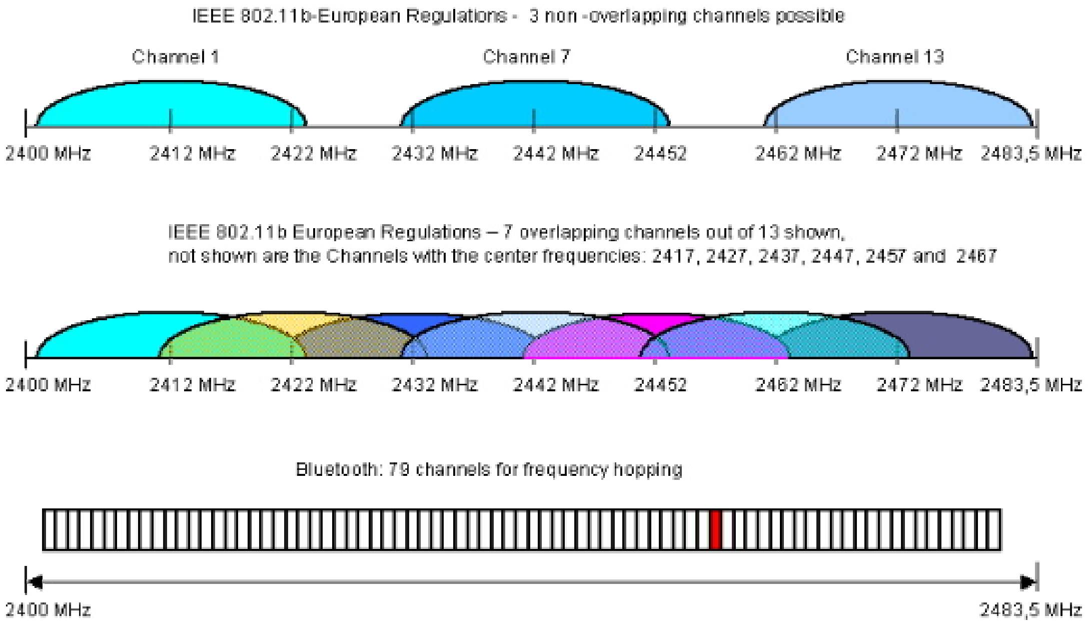

Fig 5: WLAN and Bluetooth RF channels in the ISM-Band at 2.4 GHz in most European countries

A. *WLAN interferes Bluetooth*

The impact of a 20dBm 802.11 Direct-Sequence WLAN system on a 0dBm Bluetooth link is investigated assuming a typical office environment with 2 WLAN access points.

A single access point serves 50 WLAN terminals. It is also assumed that a single Bluetooth piconet is associated with each WLAN terminal. Because of the distance between the WLAN terminals and the low Bluetooth transmit power, the mutual interference [4] between Bluetooth piconets is ignored. The performance of the Bluetooth terminal is determined by the intended power received and the interfering power received, or the total C/I. This in turn will depend on:

- The distance between the Bluetooth receiver and Bluetooth transmitter.
- The distance between the Bluetooth receiver and the WLAN terminal transmitter.
- The distance between the Bluetooth receiver and the WLAN access point transmitter.

When transmitting in its 22 MHz channel, the WLAN system effectively occupies about 17 MHz of the 2.45 GHz ISM band (20dBm bandwidth) [7]. When the Bluetooth receiver hops in the WLAN band, it filters out the Bluetooth hop bandwidth and the WLAN signal is regarded as white noise. Assuming a 0.85 MHz noise bandwidth in the Bluetooth receiver, a filter suppression of 13dB is achieved. With a C/N required of 17dB at the rate of 10^{-3} BER, the required C/I towards a WLAN transmitter amounts to 4dB. The Bluetooth system transmits with a 0dBm power level. The 20dB transmit bandwidth is 1MHz.

For the range of interference, it's distinguished between voice and data performance. The Bluetooth data channel applies re-transmission and can therefore cope with a higher packet erasure rate (PER) than voice. For the performance thresholds (the thresholds where still acceptable performance is experienced), PER=10% for data and PER=1% for voice is chosen. These two values must be considered with care since the user experience is largely determined by the time period the interference lasts. For example, a 2% PER for a period of 10 seconds in a voice connection will be more annoying to the user than a 10% PER in a period of 100ms.

Under normal traffic conditions in the WLAN, the Bluetooth voice user is not affected as long as his operating distance remains below 2m. If the distance increases to 10m, the probability of interference on the link increases to 8%. The Bluetooth data link allows and experiences more degradation. A throughput reduction of more than 10% occurs with 24% probability at an operating distance of 10m. However, because of the limited frequency overlap of the WLAN and Bluetooth systems, the throughput reduction in the Bluetooth system can never exceed 22%, if only one WLAN system is installed.

V. CO-EXISTENCE OF BLUETOOTH AND WLAN

WLAN dominates in the area of data connectivity, with the implementation of the wireless Ethernet. Bluetooth dominates in the "PAN" domain, interconnecting all devices of one's personal sphere. Bluetooth has also implemented voice support. The Specifications of both systems describe how the technology works [14]. While the WLAN architecture only covers the lower layers 1-3, Bluetooth covers the whole range from layer 1 (radio) to layer 7 (applications). A visualization of the Bluetooth protocol architecture is provided in figure 6.

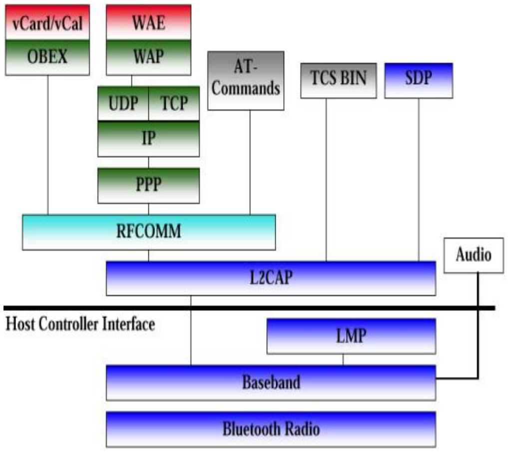

Fig 6: The Bluetooth protocol architecture

So, from this, co-existence of WLAN and Bluetooth is clear. The comparison of both the technologies (table 3) will make this clearer [9].

TABLE 3
COMPARISON OF BLUETOOTH & WLAN

	Bluetooth	**WLAN**
Data rate	4-700 kbps	4-6 Mbps
Range	10 - 100 m	100 meter
Simultaneous users	7	10 – 50
Frequency band	2,4 GHz	2,4 GHz
Transmitt power	1, 2.5, 100 mW	100 mW
Interfaces	ADSL, Ethernet, ISDN, PSTN, USB, RS232	Primary Ehernet
Support for voice	Yes	Only VOIP
Type of clients	Inbuilt in PC, PDA, Mobile Phone, CF-card, SSD-card, USB dongle, RS-232 Dongle	Inbuilt in PC, PC-card, CF-card, RS-232 dongle and Ethernet dongle
Power management	Yes	Proprieatairy solutions

VI. TOWARDS A SOLUTION

In the case of BT (half-duplex system) voice traffic, slots are allocated according to a deterministic pattern; for instance, for each SCO connection using a HV3-type link [17], a single-slot packet is transmitted periodically in both directions every six time slots. Whenever a BT packet hops in the 802.11 frequency band, an 802.11 station in receive mode1 senses the BT transmission as colored noise, i.e., as a signal with a specific behavior in time and in frequency. In a non-collaborative setting, an 802.11 station can detect the time intervals that are occupied by interfering transmissions, by monitoring the channel [12]. If SCO and ACL links are simultaneously active on the BT channel, this solution is also applied and the probability that an ACL packet hops on the 802.11 band becomes negligible. This implies that an 802.11 station is likely to detect interference due to the BT voice traffic only. Due to the periodicity and the predefined time duration of the BT voice packets, the 802.11 device can easily estimate the interference pattern. Whenever an 802.11 station is ready to transmit, it acts accordingly to the information acquired on the interference pattern. If the channel is idle and no interference is expected for a time period equal to the next $(i-1)$ BT slot duration, the 802.11 station transmits a data packet with payload size equal to the minimum of $(i.500)$ bytes and 1500 bytes. The minimum payload has been set to 500 bytes to make the corresponding 802.11 packet transmission time comparable to the duration of a single-slot BT packet. Conversely, if the channel is occupied by an interfering signal, the WLAN station can either *(i)* send a packet with a 500 bytes payload (Shortened Transmission (ST) mode) or *(ii)* refrain from transmitting (Postponed Transmission (PT) mode).

With the ST mode, the 802.11 transmission does not necessarily overlap in time with the BT packets because a 1-slot BT packet lasts just slightly longer than half the duration of one time slot. Besides, even in the case of time overlap, 802.11 and BT packets collide only if BT packets hop on the WLAN frequency band.

When a WLAN station refrains from transmitting, i.e., it acts in PT mode, the 802.11 transmission is postponed by computing a new back-off time. In this case, two opposite effects take place: (i) a lower overlap probability is achieved than in the case where a short packet is transmitted; (ii) the WLAN stations' access delay increases and the WLAN channel utilization decreases with respect to the case where the ST mode is applied.

VII. CONCLUSION & FUTURE WORK

In this paper, the problem of mutual interference & co-existence between Bluetooth & WLAN operating in the 2.4 GH ISM bands were addressed. One co-existence mechanism based on traffic scheduling techniques was proposed: (named V-OLA scheme) to be applied at the WLAN stations to avoid overlap between 802.11 traffic and Bluetooth voice packets. The main advantages of the proposed mechanism are: 1) they do not require a centralized traffic scheduler; 2) they can be implemented using either collaborative coexistence or non-collaborative coexistence mechanism.

In the case of two Bluetooth voice connections, an improvement of about 20% both in the 802.11 and the Bluetooth goodput was achieved, while the additional delay introduced in the 802.11 data transfer was of the order of tens of milliseconds. In the case of Bluetooth data traffic, the 802.11 goodput increased by 50% for high Bluetooth traffic load; whereas, for high 802.11 traffic load, the Bluetooth goodput improved of 24% without showing a significant increase in the data transfer delay.

There are many thing those need proper attention. The aspects those need to be addressed in future research are as follows.

1. Exploring the possibility to enhance the physical layer of unlicensed devices so that their ability to detect interference generated by other technologies is improved.
2. Coexistence between Bluetooth and 802.11 systems that implement the PCF MAC scheme.
3. Performance study of the proposed techniques through experimental measurements.
4. Impact of the proposed mechanism on the interference between coexisting Bluetooth piconets.

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